(54) Converter for switched reluctance motor

(57) In a converter for a switched reluctance motor SPSR, the d.c. link includes a series diode D_b and a shunt capacitor C_b which form a voltage boosting circuit. The boosting circuit enhances the performance of the converter by providing a high boost voltage during the current pull-up and pull-down periods and hence decreasing the current rise and fall time. The converter can be in the form of a half-bridge inverter for a single phase switched reluctance motor SPSR or a polyphase switched reluctance motor (Fig 11b) or can be in the form of an inverter for a polyphase bifilar switched reluctance motor (Fig 11a).
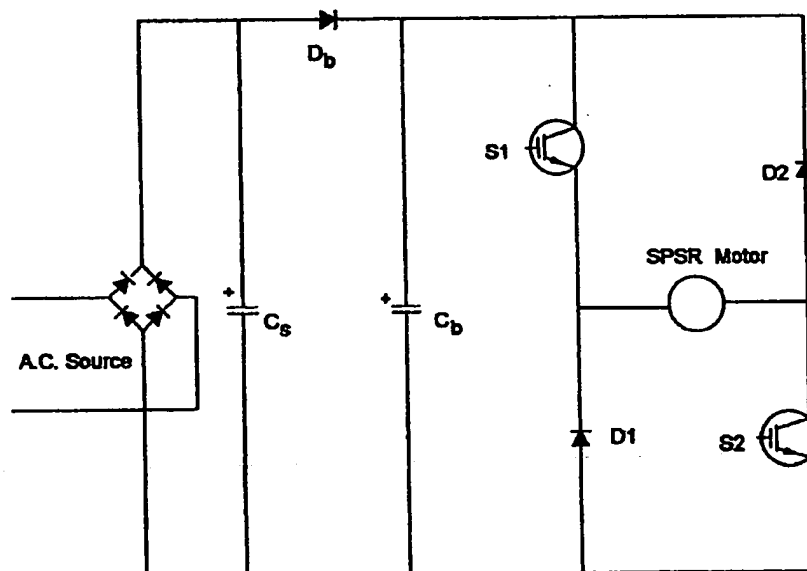
Fig. 2

GB 2 273 212 A
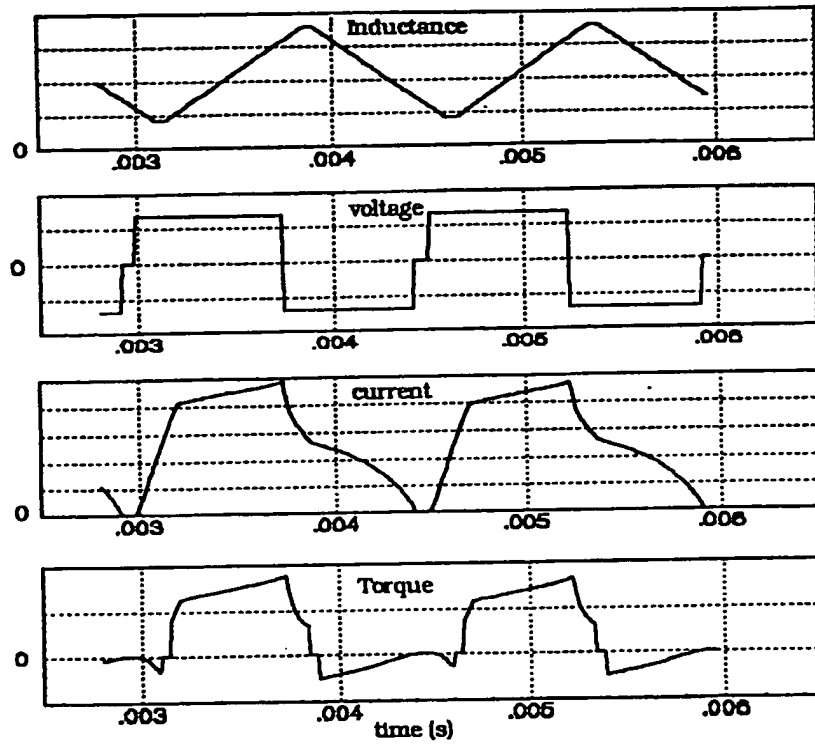
Fig. 1   Performance of unsaturated SPSR Drive
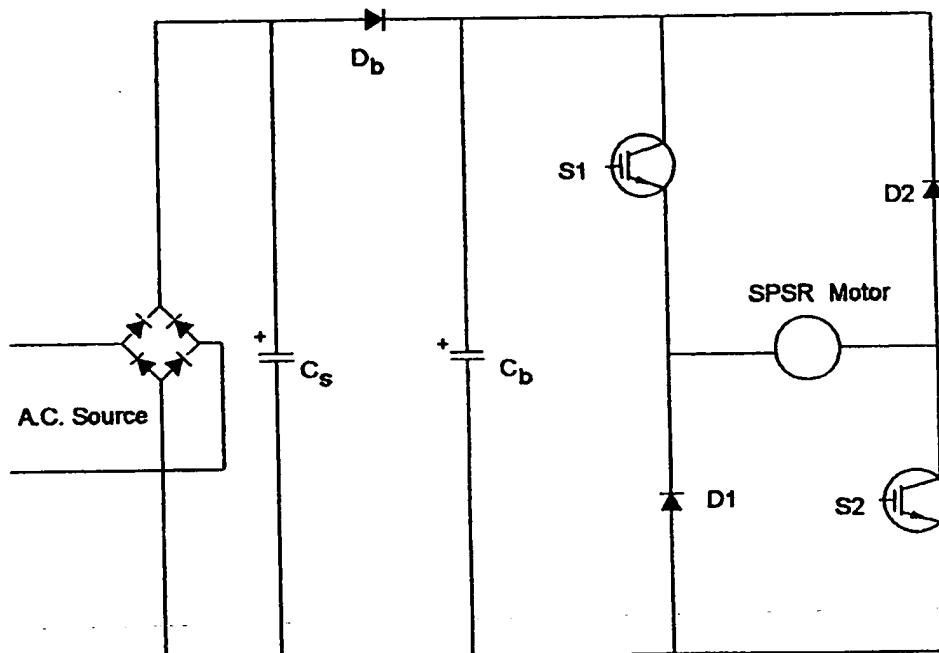
Fig. 2   Boosted asymmetric half-bridge inverter
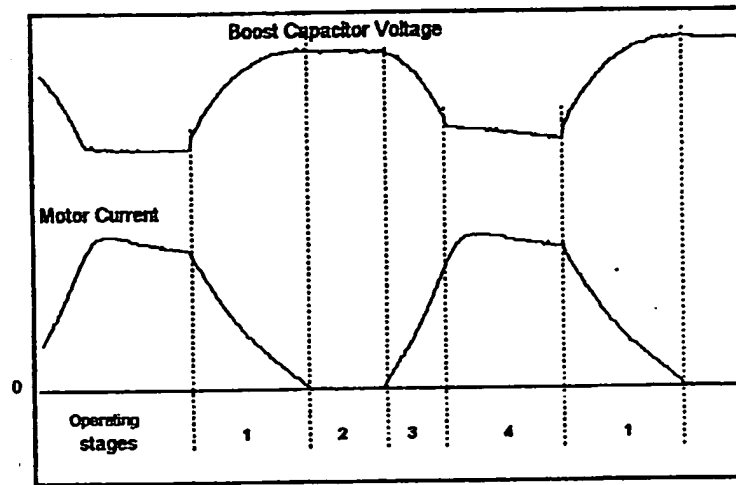
Fig. 3. Operation of Boosted SPSR Drive
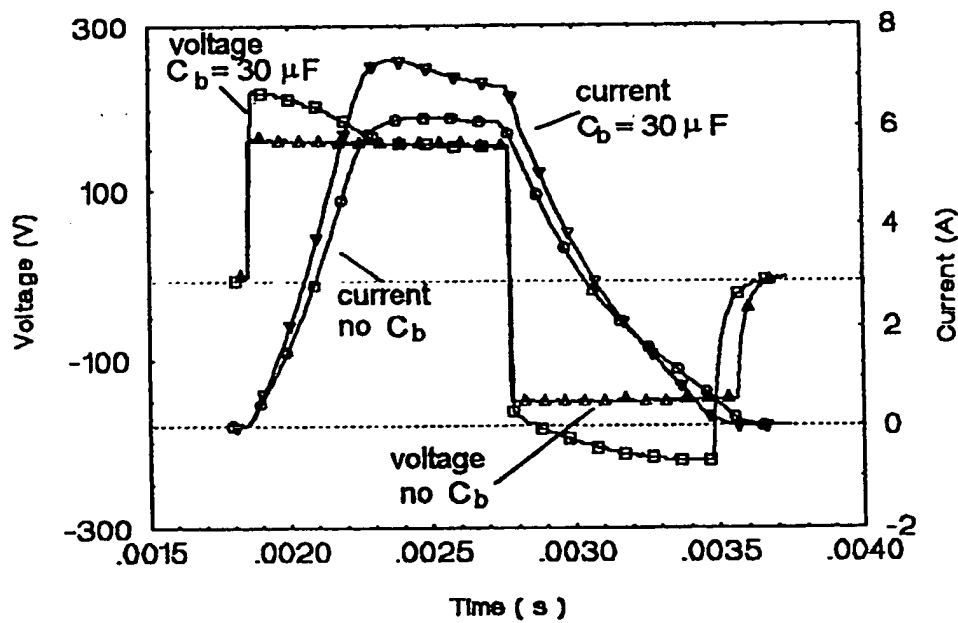
Fig. 4 Boosted and non-boosted drive operations
Speed = 16300 rpm, Link voltage = 150 V
$\alpha = 38.4°$ $\beta = 39.7°$
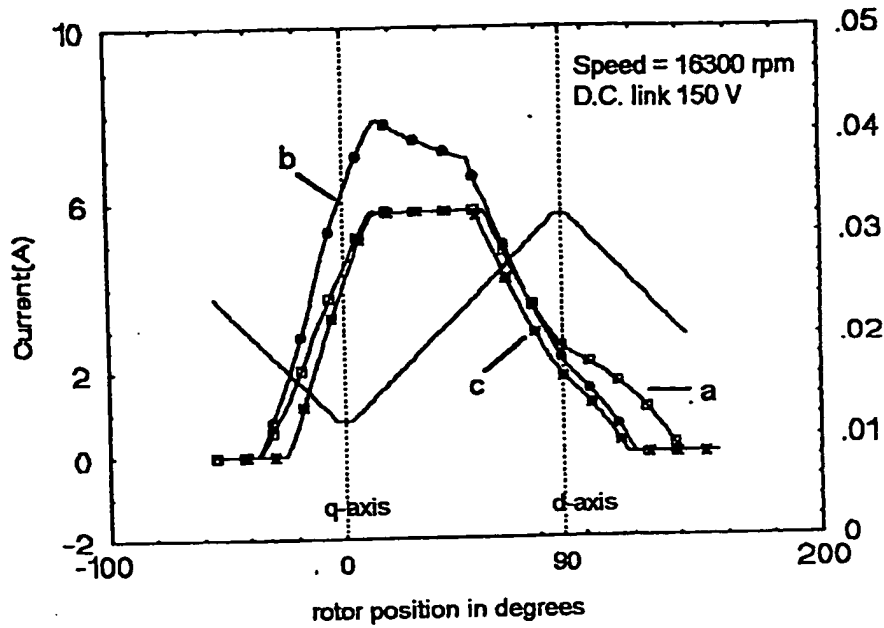
Fig. 5 Boosted currents at different sets of switching angles

a : No boosting, $\alpha = 38.4^\circ$, $\beta = 39.7^\circ$, power = 120 W

b: $C_b = 30\ \mu F$, $\alpha = 38.4^\circ$, $\beta = 39.7^\circ$, power = 185 W

b: $C_b = 30\ \mu F$, $\alpha = 23.0^\circ$, $\beta = 36.0^\circ$, power = 120 W
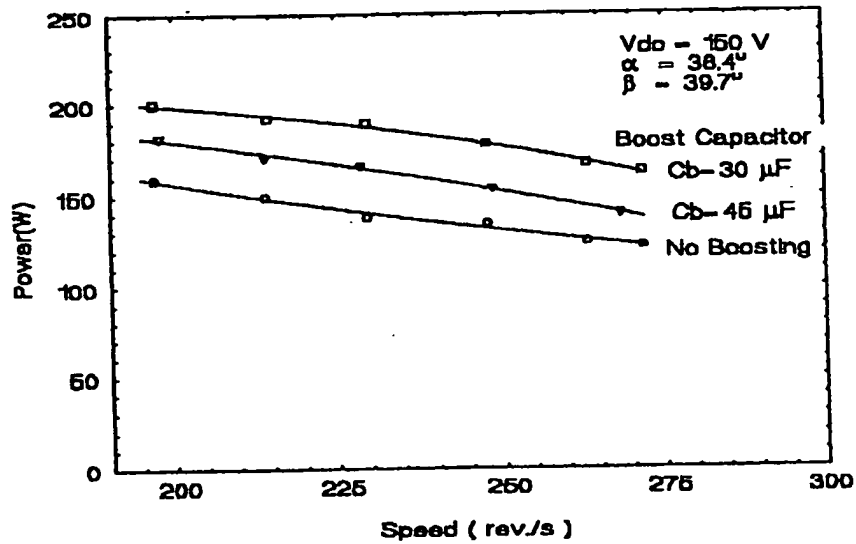
Fig.6 Measured output power at different levels of boosting
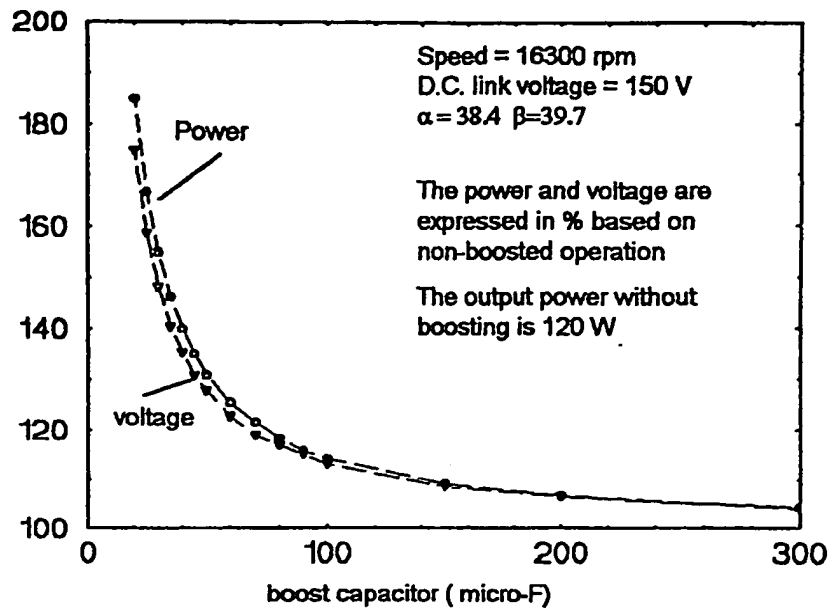
Fig. 7 Boosted drive performance versus boost capacitor size
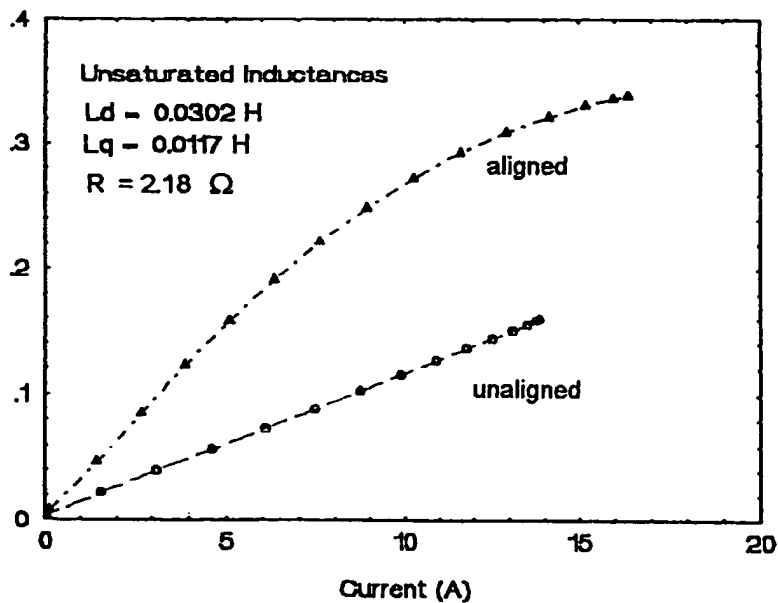
Fig. 8 Ψ - i Characteristics of test motor

stator pole width 84 °

rotor pole width 90 °
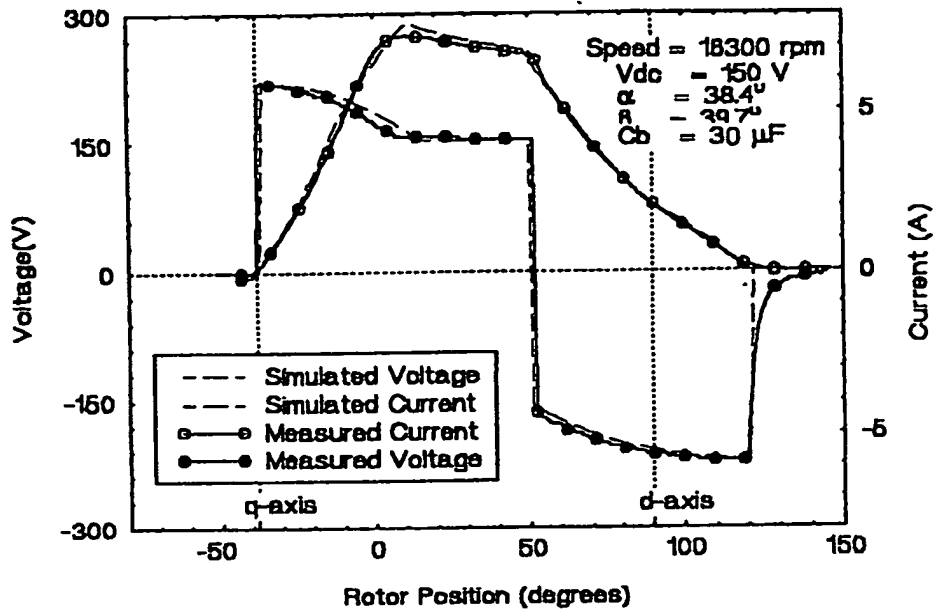
Fig. 9   Measured and predicted current and voltage
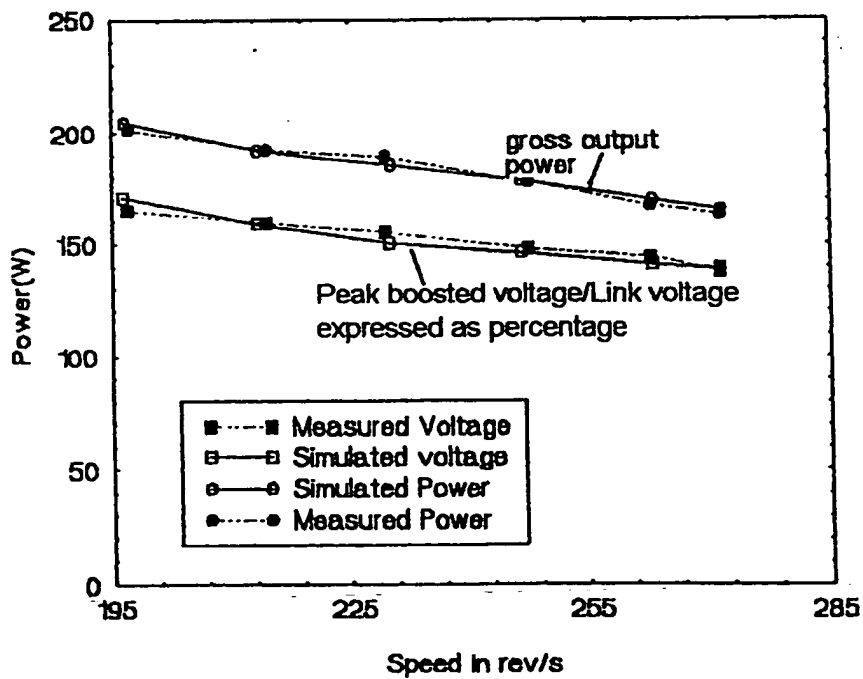
Fig. 10. Measured and predicted output power
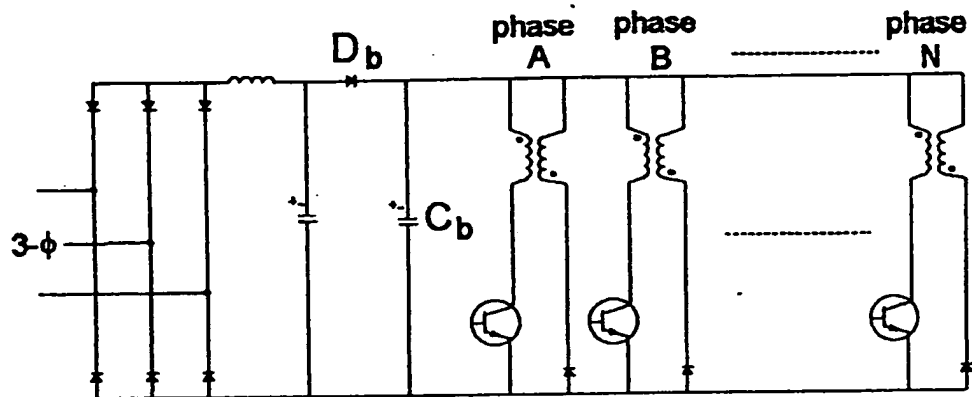
Fig. 11(a)   Boosted polyphase bifilar SR inverter
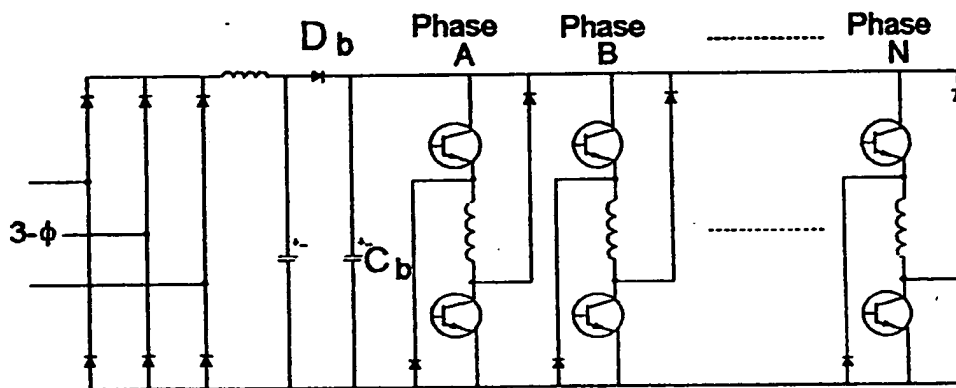
Fig. 11(b) Boosted asymmetric half-bridge SR inverter

Voltage Boosting Arrangement for Switched Motor

This invention relates to a voltage boosting arrangement for a switched motor, and more particularly to a d.c. link voltage boosting circuit to enhance the performance of converters (particularly inverters) for switched reluctance motors.

1. List of Figures of accompanying drawings

2.   List of Symbols

ω motor speed in revs./s.

V   D.C. link voltage

V_b boost capacitor voltage

i   motor instantaneous current

Ψ flux linkage of motor phase winding

L(t)   inductance of phase winding

L_d direct axis inductance

L_q quadrature axis inductance

k_1 Inductance ratio defined as $1 - L_q/L_d$

R   resistance of phase winding

C_b voltage boosting capacitor

α switching on advance angle w.r.t. q-axis

ß   switching off advance angle w.r.t. d-axis

Ω_s stator pole arc in degrees

Ω_r rotor pole arc in degrees

Ω_d $(\Omega_r - \Omega_s)$

X_β The subscript β is used to denote quantities at the instant of commutation

3. Introduction

The simple and robust features of the polyphase switched reluctance motor (SRM) have attracted much interest amongst researchers[1,2,3,4] and polyphase SR drives are now reasonably well established commercially. Single phase versions of switched reluctance motors(SPSRM) can be made but they produce a

torque that is inherently discontinuous and are hence only suitable for applications insensitive to torque-ripple and having easy starting conditions. However, the single phase SR motor has received a modest amount of attention because of the opportunities afforded for particularly simple and economic motor constructions and feed circuits. In 1979 Bolton and Pedder[5] investigated the viability of a single phase switched reluctance motor restricted to low speed use. The motor used a 6:6 configuration with a radial/axial flux path, a simple circular excitation coil, an external rotor and a cylindrical layout. In 1981 Chatratana and Bolton[6] proposed three further SPSRM configurations, and described the asymmetric half bridge and bifilar pull-down feed configurations. The three motor configurations, all of them using a 2:2 pole arrangement, employed (i) a 'C'-core magnetic circuit with a single bobbin excitation coil, (ii) a conventional 2 pole stator with 2 concentrated coils, and (iii) radial/axial flux paths with a single circular excitation coil and an axially-laminated rotor. Test results for speeds up to 21000 rev./min were reported. Compter's 1984 paper[7] described the use of microprocessor for controlling the SPSRM while in 1983 ,Chan [8] proposed a modified form of the motor reported in [4] and investigated its design trade-offs.

A number of patents involving or relevant to single phase SR motors have been granted since 1976. The patents known to the authors of the present paper deal with three areas: constructional and circuit features for starting by 'axis shifting', control and sensing schemes and novel motor configurations. Patents dealing with starting features describe different ways in which the rotor orientation for maximum inductance can be shifted somewhat with respect to its normal orientation through the use of a non-symmetrical saturation distribution in the stator or rotor poles. Reference 9 proposes the use of dissimilar stator poles, reference 10 the use of a stepped gap on the rotor poles, reference 11 the adoption of stator pole shaping, namely side slits and pole horns, reference 12 the

shaping of both stator and rotor poles, and reference 13 the use of smoothly graded air gaps by stator pole shaping. In each case the starting orientation of a lightly-loaded rotor can be swung by increasing the current from a value giving a symmetrical flux axis to a value giving rise to a non-symmetrical saturation distribution and a shifted axis. By appropriate current pulsing, rotor orientation sensing and control, the motor can be started even when the rotor's initial orientation lies along the normal d-axis. In general, these proposals are suitable for starting in one direction only, although with sophisticated control schemes, reverse rotation can be effected.

Reference 14 proposes a circuit arrangement for sensing of rotor orientation without the need for a sensor as such, in which the e.m.f. due to residual flux or a specially-introduced bias current is picked up. Reference 15 describes in some detail a circuit arrangement for starting, speed control, and the maintenance of synchronism using a microprocessor and simple rotor orientation sensor.

Finally references 16-17 propose novel motor configurations. Reference 16 outlines a SPSR disc motor in which the motor construction is integrated with that of the load, in this case a pump. Reference 17 describes a 4:4 SPSR configuration with two coils and short flux paths giving reduced iron weight and iron losses.

The basic torque producing mechanism of a SPSRM is, of course identical to that of its polyphase counterpart. However, in the former the angular momentum of the rotor and load are relied on to maintain motion during the periods of decreasing stator to rotor tooth alignment when the production of positive torque is impossible. The basic operation can be described by assuming that the inductance of the phase winding varies with rotor angle in a trapezoidal fashion[3] as shown in figure 1(a). The instantaneous torque of a magnetically

linear SRM at rotor position θ is given by $T(\theta) = \frac{1}{2}i(\theta)^2 \frac{dL(\theta)}{d\theta}$. Hence, if the inverter voltage is applied to the motor when the rotor is at the q-axis and removed when the rotor reaches the d-axis, a positive torque pulse is produced. In practice, however, it is found that to obtain a reasonable high mean torque, it is often desirable as with polyphase SR motors, to control the feed so that the link voltage is applied to the winding somewhat before the q-axis position is reached and removed before the d-axis position. In other words, it is necessary to advance the switching angles appropriately to maximise the motor output. Typical voltage, current and torque curves for conditions giving the so-called 'flat-topped' current operation are shown in fig 1.

Current flow during periods of negative $\frac{dL}{d\theta}$ is almost inevitable and gives rise to negative torque pulses during the current pull-up and current pull-down periods. The magnitude and duration of these negative torque pulses could be reduced if the positive and negative $\frac{di}{dt}$ during the pull-up and pull-down period could somehow be increased. The use of fewer turns in the motor winding to reduce the inductances would, of course, generally be self-defeating since the motor torque would fall unacceptably as indicated by the above torque relation. If, however, there was some way of raising the inverter voltage temporarily, the current pull-up and pull-down times could be reduced without reducing the motor output. Ideally, what is needed is a voltage higher than the nominal inverter voltage, that is a boost voltage, during the current pull-up and pull-down periods only. The higher the boost voltages, the higher the $\frac{di}{dt}$ will be.

Boost voltages could be particularly beneficial for low voltage battery fed SPSR drives, and also for high speed SPSR drives. With low voltage drives, there is little risk of the increased voltage leading to the need for inverter devices

with increased voltage rating since with the typical rail voltage of 6, 12 and 24 volts there is likely to be plenty of voltage rating in hand. For high speed applications, on the other hand, motor power tends to be limited by the high value of speed-voltage so that voltage boosting could hence significantly increase a drive's maximum speed capability when driving a typical load.

One obvious way to generate a voltage higher than the inverter nominal voltage is to use some form of capacitive voltage boosting feature. Capacitive voltage boosting schemes have appeared in the SR literature, but except for a recent circuit proposed by Hoang[18], all involve dual rail topologies[19]. The boost features of typical boosted dual-rail inverters consist of a boost capacitor connected to the second rail which is separated from the d.c. link rail via a power switch and a smoothing inductor. The power switch, of course, facilitates the provision of active control for the boost process but will require additional control logic. The circuit proposed in [18] involves some re-arrangement of the asymmetric half bridge switches and requires a boost capacitor for each phase. This modified half bridge inverter however, requires for active current control, an extra power switch connected in series between the d.c. link and the modified half bridge.

At UWCC, the authors' work on the SPSRM is based on the single-rail half-bridge configuration[5], and effort is directed to enhance the output of this type of drive. A novel and simple boost circuit is proposed in this paper.

4. The Voltage Boosting Feature

The voltage boosting feature is illustrated in figure 2. The two extra components in the feed circuit comprise a power diode D_b and a voltage-boosting

capacitor C_b. Typical voltage and current wave forms of a boosted SPSR drive are given in figure 3.

Inverter operation with this feature can be divided into 4 stages.

Stage 1: Involves current pull-down through diode D1, D2 and the charging of the boost capacitor C_b.

When S1 and S2 are turned off, the motor winding current is forced to flow into the boost capacitor by the boost diode D_b and thereby to raise the voltage of C_b rapidly above the link voltage. The motor circuit is effectively isolated from the d.c. link by D_b and operates as an R-L-C circuit. Current is pulled down rapidly by the rising capacitor voltage. Current reversed is prevented by the two commutating diodes D1 and D2.

Stage 2: Motor current at zero.

With S1 and S2 off, the motor winding is fully de energised. There is no motor current and the boost capacitor hence maintains its full boost voltage.

Stage 3: Involves the energisation of motor winding from boost capacitor through S1 and S2.

At the start of next switching cycle, S1 and S2 are turned on, and the motor current is forced to rise rapidly by the high initial boost voltage on C_b

Stage 4: Involves the energisation of motor winding directly from the d.c. link.

This stage starts when the boost capacitor has discharged to the level that its voltage is sufficiently low to forward bias

the boost diode. The current is then supplied directly from the d.c. link.

In practice since the time constant RC_b is quite small, the impact of the boost circuit on motor and inverter voltage is confined virtually to the current rise and fall periods. If the voltage rating of the switching devices is adequate, the boost feature does not require constructional changes to the inverter itself or to the control hardware. Active control of the boost process is, of course, unnecessary because the active or inactive state of the boost feature occurs naturally through the presence of the boost diode D_b.

There are two ways in which the boost feature action can be used to enhance the operation of a SR drive. Firstly, the high boost voltages during current pull-up and pull-down provide the opportunity to reduce the switching advance angles, thereby achieving more efficiently the same output power as the non-boosted drive as discussed previously in the introduction. Secondly, the optimum switching angles of the non-boosted drive may be retained to allow the boost feature to raise motor current and the mean output power appreciably. A power boosting of up to 50% would seem to be realisable by proper sizing of the boost capacitor.

The inclusion of the boost feature is thus likely to result in a reduced speed ripple, an increased mean output power, improved energy recovery and a higher feasible operating speed. Since the boost diode isolates the motor from the d.c. link for a large portion of each cycle, the d.c. link ripple voltage is reduced and the effect of the phase current pulses on the a.c. main is lessened.

As far as current control is concerned, it is still feasible for the SR half-bridge inverter to pulse width modulating one or both the power switches. If both the power switches are modulated, the frequency of the current PWM control will be increased slightly by the boost feature. However, if only one of two power

switches is modulated, the motor current will decay in a zero-voltage loop formed by a power switch and a commutating diode. Since there is no interaction between the zero voltage loop and the boost capacitor in this situation, the boost circuit will have no effect on the PWM current control.

The scheme's benefits need to be set against its costs which are (a) the requirement for a higher voltage rating in all inverter components except the d.c. link rectifier and smoothing capacitor, and (b) the need for a power diode and a high voltage boost capacitor. The present industrial trend is to standardise the voltage rating of power switching components for a.c mains application to 600 V. This will inevitably lead to increasingly competitive pricing of components at 600 V rating. With power switches rated at 600 V, a power and voltage boost of up to 50% can be feasible with 240 V a.c. fed drives (giving approximately 340 V d.c. rail) subject to thermal limits in the motor and devices. Since the cost of the boost capacitor and diode is typically about 10% of total feed cost of the single phase drive, the scheme would seem to be cost effective. Of course, it would generally be preferable to design the boost feature as an integrated part of a drive system from the start, rather than as an add-on feature, since this would enable the size of the motor to be reduced.

5. Impact of the boost feature on measured drive performance.

Illustrated in figure 4, 5 and 6 are comparisons between typical measured results of a high speed single phase switched-reluctance motor drive operated with and without the boost feature. The magnetic characteristics of the motor are given in figure 8. Figure 4 illustrates a typical voltage wave form produced by the boost feature. Figure 5 illustrates how the boost feature reduces the rise time and fall time of the motor current appreciably and produces a higher motor mean current without the need for a higher supply voltage. Figure 5 also indicates that

for the same output power, the addition of the voltage boosting feature allows the use of smaller advance switching angles.   Figure 6 compares the drive's measured output powers with and without the boost feature using identical sets of switching angles.   All measurements were carried out with the same A.C. source voltage. The effect of boost capacitor size on mean output power and peak boost voltage, as estimated by simulation, is shown in fig. 7. The figure clearly indicates that the smaller the boost capacitor size the higher is the boost voltage and power.

6. Sizing of boost capacitor

The peak voltage at the end of the boost period (stage 1) depends on the boost capacitor size and the magnitude of inductive energy stored in the motor magnetic circuit at the instant of turn off. If losses are neglected, the stored field energy at this instant will be all transferred to the boost capacitor by the end of stage 1. The stored field energy is .

$$E_s = \int_{\Psi_\beta}^{0} I \, d\Psi$$

Where the subscript β indicates value at turn off.

The stored energy in the boost capacitor is increased by

$$E_c = \tfrac{1}{2} C_b \left(V_2^2 - V_\beta^2 \right)$$

where V_β is the boost capacitor voltage at turn off and V_2 is the final boost capacitor voltage.

Equating these two energies gives

$$C_b = \frac{2 \int_{\Psi_\beta}^0 i\, d\Psi}{(V_2^2 - V_\beta^2)} \hspace{1cm}\text{——————————— (1)}$$

Equation (1) is valid for both linear and non-linear operations. For magnetically non-linear operation, the field energy is difficult to evaluate analytically and hence the estimation of C_b for a desired boost voltage V_2 requires time-stepping simulation.

However, if the magnetic circuit is assumed to be linear, the field energy is $E_s = \frac{1}{2} L_\beta I_\beta^2$ and equation (1) then simplifies to

$$C_b = \frac{L_\beta I_\beta^2}{(V_2^2 - V_\beta^2)}$$

The current at the instant of commutation I_β is generally difficult to estimate. However, if the motor is operated with a switch-on angle producing a flat-top current, the current I_β is often equal to the maximum current which can be approximated as $I_\beta = V/\frac{dL}{dt}$. With motor inductance modelled as a trapezoidal function of rotor position, L_β, I_β and C_b can be estimated as follows:

$$L_\beta = L_d \left(1 - k_l (\beta - \Omega_d/2)/\Omega_s \right)$$

$$I_\beta = \frac{V_\beta \, \Omega_s}{360 \, \omega \, k_l \, L_d}$$

$$C_b = \frac{1 - k_l (\beta - \Omega_d/2)/\Omega_s}{\left(k_v^2 - 1 \right) L_d} \left(\frac{\Omega_s}{360 \, \omega \, k_l} \right)^2 \hspace{0.5cm}\text{———(2)}$$

where k_v is defined by $V_2 = k_v V_\beta$

Unfortunately, the value C_b estimated by equation (2) is not very close to the value corresponding to practical operation with a reasonably saturated motor. It is, however, useful as an initial value for the subsequent accurate sizing of C_b by time-stepping simulation.

7. Simulation of boosted SPSR Drive

As with other SR motors, the operation of the SPSRM can only be assessed realistically by time-stepping simulation. The governing differential equations for a SPSRM operated from a boosted d.c. link are

$$\frac{d\Psi(i,\theta)}{dt} = V_b - iR \qquad \text{——— (3)}$$

where $\Psi(i,q)$ is a non-linear function

$$\frac{dV_b}{dt} = -i / C_b \qquad \text{——— (4)}$$

Equation (4) models the boosting process and its solution exists only for the stages 1 and 3 described in section 4. During stage 2 and stage 4, no current flows into the boosting capacitor, so equation (4) is irrelevant and V_b is equal to the voltage of the d.c. link.

Since the term iR in equation (3) typically amounts to only a few per cent of V_b, $\frac{d\Psi}{dt}$ is not sensitive to the prediction error in the current and hence the flux linkage Ψ can be compute quite accurately by integrating equation (3) numerically. In fact, the current is more difficult to compute accurately due to the highly non-linear $\Psi - i$ characteristics of switched reluctance machines. For

accurate predictions of the motor current, the $\Psi - i$ relations for large number of rotor positions would normally need to be determined from extensive tests or finite element analysis. The authors, however, have used the recently proposed method by Miller[20] for its simplicity combined with minimal sacrifice in accuracy. The method requires only the $\Psi - i$ curves for rotor positions at d-axis and q-axis only. These two $\Psi - i$ curves together with motor dimensional information are used to evolve $\Psi - \theta$ relations with the current as parameter[20,21]. The details of the modelling algorithms are given in [14] and will not be repeated here. Equations (3) and (4) are solved numerically by a simple Euler formulation. The flux linkage $\Psi(i,\theta)$, at a new time step is estimated from (3) using the current and the boost capacitor voltage at the previous time step. The current at the new time step is approximated from the $\Psi - \theta$ relations of the machine by interpolating between the Ψ for the aligned and unaligned rotor positions using $\Psi(i,\theta)$ at the new time step. When the boosting process is active, the boost voltage for the new time step is then estimated from (4) using the current at the previous time step. When the boosting process is inactive, the voltage V_b is set equal to the d.c. link voltage. In studies done so far, the d.c. link voltage has been assumed to be constant to simplify the simulation algorithm.

8. Comparison of measured and simulated results

A SPSRM capable of 20000 rev/min was built and tested. The measured magnetic characteristics of the test motor with the rotor at the d-axis and q-axis positions are given in figure 8. All the machine parameters used in the time-stepping simulation were derived from the information given on figure 8. Figure 9 compares the measured and calculated voltage and current wave forms at 16300 rev/min with a 110 V A.C. source voltage. Figure 10 compares the measured and calculated gross output power at various speeds with identical switching angles.

To simplify the comparison of measured and calculated quantities, all measurements were taken without PWM current control . Figures 9 and 10 indicate excellent agreement between measured and simulated results.

9. Application of boost feature to polyphase SR motors

Any SR inverter which works satisfactorily with a single-rail d.c. source could in principle utilise the proposed boost feature. Initial assessment indicates that the boost circuit is likely to be applicable to most single-rail polyphase SR inverters. The boost circuit arrangement for a polyphase bifilar SR inverter is shown in fig. 11(a) and the corresponding asymmetric half-bridge version in fig. 11(b). Each phase of the motor still can be controlled independently as usual for normal switching and zero-voltage-loop PWM current control. Since the boost feature still consists of a capacitor and a diode, its cost impact in polyphase applications should be relatively small.

The polyphase boosted drive can still be operated with current overlap between phases as usual. It is, of course, true that if the period of current overlap between phases is approximately equal to the commutation period of the de-energising phase, the boost voltage could be insignificant. In practice, however, the duration of the current overlap between phases is usually short compared to the commutation period. A correspondingly large portion of the de-energising phase winding energy would still be transferred to the boost capacitor and hence a significant boost effect would be maintained.

The boost feature could also be applicable to other non-standard SR inverters[22, 23]. Its operation in such cases is, however, likely to be restricted by the inherent limitations of such inverters with their 'minimum components' configurations.

10. Conclusion

A novel and simple voltage boosting feature has been proposed to enhance the performance of switched-reluctance motors inverters fed by single-rail supplies. The implications of the boost feature for the inverter and motor performance have been discussed. Increases of more than 50% in inverter voltage at the start of the current rise period and in motor output power would seem to be realisable. Methods of sizing the boost capacitor and time step simulating the boosted drive have been examined. The measured and simulated results presented correlate closely.

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Claims

1) A converter for a switched reluctance motor, the d.c. link of the converter including a series diode and a shunt capacitor which form a voltage boosting circuit.

2) A converter as claims in claim 1, in the form of an asymmetric half-bridge inverter for a single phase switched reluctance motor.

3) A converter as claimed in claim 1, in the form of an inverter for a polyphase bifilar switched reluctance motor.

4) A converter as claimed in claim 1, in the form of an asymmetric half-bridge inverter for a polyphase switched reluctance motor.

5) A converter for a switched reluctance motor, the converter being substantially as herein described with reference to Figure 2, Figure 11(a) or Figure 11(b) of the accompanying drawings.

Patents Act 1977 E~ ~niner's report to the Comptroller under Section 17 (1~~ Search report)	Application number GB 9324615.5

Relevant Technical Fields
 	
(i) UK Cl (Ed.M)   H2J (JCSR, JEST, JETR, JEX, JSSS, JSVP,
                         JSVF, JMLC) H2F (FDACS, FDACT,
                         FDACX, FDAXS, FDAXT, FDAXX, FFCS,
                         FFCT, FFCX, FMX)
	Search Examiner
	B J EDE

(ii) Int Cl (Ed.5) H02P H02M	**Date of completion of Search** 9 FEBRUARY 1994
Databases (see below) (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii) ONLINE DATABASES: WPI	Documents considered relevant following a search in respect of Claims :- 1-5

Categories of documents

X:	Document indicating lack of novelty or of inventive step.	**P:**	Document published on or after the declared priority date but before the filing date of the present application.
Y:	Document indicating lack of inventive step if combined with one or more other documents of the same category.	**E:**	Patent document published on or after, but with priority date earlier than, the filing date of the present application.
A:	Document indicating technological background and/or state of the art.	**&:**	Member of the same patent family; corresponding document.

Category	Identity of document and relevant passages	Relevant to claim(s)
X	US 5119283 (STEIGERWALD ET AL) - see 16, 18 Figures 1 and 2	1
X	US 5115181 (SOOD) - see X4, C1 Figure 3	1-4
X	US 5038267 (DE DONCKER ET AL) - see Db, Cr Figures 1, 6, 8a-8c	1-4
X	US 4934822 (HIGAKI) - see 3, 73 Figure 3	1
X	US 4855652 (YAMASHITA ET AL) - see 3, Figures 1 and 5	1-4

Databases:The UK Patent Office database comprises classified collections of GB, EP, WO and US patent specifications as outlined periodically in the Official Journal (Patents). The on-line databases considered for search are also listed periodically in the Official Journal (Patents).